Thermal analysis and PCB Design for a GaN Power Transistor

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*Abstract*— A more reliable, efficient and interconnected grid system is what we are heading towards. Most of modern power system technologies like wind, solar and electric vehicles depend on power inverters. Making them smaller and more efficient brings many challenges, but at the same time improvements that can revolutionize our electric driven world. One of the most important aspects in power inverter is the management of heat to improve performance, life, and reduce failure rate. Semiconductors play an important role in power inverters because of their performance boost, decrease power loss, and thermal management characteristics. This paper will talk on the thermal analysis for a PCB design, emulating the use of a GaN power transistor in a small power inverter prototype. It will be compared to simulations made on FEMM as well as theoretically. Different simulation models will be compared to see if the original prototype is the best design for thermal heat management.

*Index Terms*— Thermal analysis, PCB, GaN, Power transistor, heat management

# Introduction

As we move forward technology keeps evolving and devices keep getting smaller and faster. Much of what we hear these days is how we are moving towards a new “smarter grid” that is more efficient, cleaner and integrated with ours homes and cars. According to research made by “Green Tech Media (GTM)” the United States is installing one photovoltaic system every four minutes. If current trends continue to grow at the same pace, by 2016 there will be a system installed every 20 seconds [1]. As of the wind energy sector, reports from the wind energy foundation website tell us that, “Wind energy is the fastest-growing source of electricity in the world, with a global installed capacity of 35,467 megawatts (MW) in 2013. In the United States at the end of September 2014, there were 62,300 MW of wind capacity operational, with more than 13,600 MW of new generating capacity under construction” [2].

DC/AC inversion technology is of vital importance for these renewable energy grid applications as well as electric vehicles, military, and others. In recent years, inversion technology has developed rapidly, with improvements in the power factor and power efficiency. Semiconductors play an important part in power inverters because of their performance boost in areas such as thermal management, and minimization in power loss. Power device such as inverters can’t rely on present silicon-based (Si) semiconductors. This is where wide band gap semiconductors like silicon carbide (SiC), gallium nitride (GaN), and diamond come into play.

One of the most important aspects in designing a small power inverter (figure1) is to manage the temperature for optimal performance and device life. For semiconductors to be able to operate at such high temperatures their band gap must be wider. As temperature increases, electrons increase their thermal energy giving them the opportunity to move to the conduction band [3]. This is a characteristic of all semiconductors that is always present and must be controlled. Semiconductors with a wider band gap can operate at much higher temperatures without losing their electrical characteristics. Gallium nitride is one of these materials that have a wide band gap of 3.4eV giving it access to applications of high power and high frequency switching. At the same time there is a high dissipation of thermal energy that comes as a result of operating at high power and it must be managed to allow it to work properly and to extend the life of the material. For the experimental prototype been studied on this project a GaN transistor is used thus the right PCB design is essential for the thermal management of GaNtransistor. There are several factors that impact the PCB thermal performance and they are the heat spreading copper layers, thermal vias, and the heat sink.

The bottom copper layer that touches the GaN transistor has the important task of spreading to other layers the heat that is been dissipated by the small area of the GaN die. The middle and top copper layers are most efficient if vias are used to transfer the heat between them. Vias are small drilled holes that can electrically connect or transfer thermal energy from one side of a PCB to the other [4]. The top copper layer transfers the heat to the heat sink. Because most PCBs use FR-4 materials there thermal conductivity is very low and thermal vias is the most effective way to improve thermal resistance. Thermal resistance is a measurement of a temperature difference by which an object or material resists the flow of heat. The design of the thermal vias has many implications; here are some ways to improve thermal energy spreading:

* Use of small via diameter. The minimum drilling size is 8 mils (0.2mm).
* The minimum copper plating thickness is of 20μm (0.8mil) even though 1 oz copper (1.4mil) is mostly used [4].
* The thickness of the PCB will also determine how well the vias perform [4].

The heat sink transfers the heat that it receives from the thermal vias. Some of the most important things to take into consideration:

* The maximum allowable case temperature around the heat sink.
* Maximum amount of power dissipation of the device been cooled.
* The maximum temperature allowed by the heat sink [5].
* Size for the heat sink.
* Use of a thermal interface material.



Figure 1: Inverter prototype

# Methodology

A. Experimental

For this experimental power inverter, two 30Ω surface mounted resistors (PWR163S-25-30R0J) in series were replaced for the GaN power transistors to be used if developed. Each resistor has the same thermal via configuration as in figure 2. The resistor is soldered and connected at the bottom of the PCB in the same way the GaN power transistor would be. An adhesive is placed under the resistor to maximize surface contact and heat spreading between the resistor and PCB vias. The PCB vias rout the heat through the four copper planes of the PCB and into the top side of the PCB. The PCB is composed of four copper planes of 1 oz (1.4mils) each. The top and bottom copper layer are connected to the other two copper layers inside the PCB by means of the thermal vias. Between each copper layer a FR-4 material composed of woven fiberglass cloth and an epoxy resin that help insulate the different layers as well as strengthen the PCB. Between the top copper layer of the PCB and heat sink a thermal interface material (TIM) is places to eliminate air gaps and to electrically isolate the heat sink. The heat sink will then be cooled by two fans to dissipate the heat to ambient.

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Figure 2: Experimental PCB configuration.

Taken from GaN systems application note.

To gather data, the use of a power supply connected in series with a digital multimeter was used to be able to look at the voltage and current passing through the resistors. Having the values for voltage and current let us know the power that will be dissipated by the two resistors in series. For thermal data acquisition the use of a thermal camera and thermometer was used. Because the thermal camera is less accurate than the thermometer, all heat sink temperature values used for the experimental analysis will be from the thermometer. To be able to gather data under the same conditions for every test, a scale from 10% to 100% (17.96 Watts been 100%) was used as basis for the heat dissipation of the resistors at different power values. By multiplying the voltage and current displayed on the power supply and multimeter and dividing the result by 18 one can find the 10 different values used (1). The resulting power values are given in table I, with 17.96 been max.

 (V)(I) = P $\frac{P}{18} =\%$ $\frac{P}{18} =\%$ (1)

Table I.

|  |
| --- |
| Power (W) |
| 17.96  |
| 16.27 |
| 14.41 |
| 12.61 |
| 10.84 |
| 9.00 |
| 7.21 |
| 5.48 |
| 3.64 |
| 1.83 |

When finding these 10 values one can start gathering data for the heat dissipation of the resistors as well as the heat sink temperature values. Connect the thermometer at the top of the resistor as shown in figure 2 to gather the most accurate temperature values. For the heat sink three different locations where used to gather measurements and compare. Figure 4 shows the locations used to gather the data. After placing the thermometer in the resistor and choosing a location for the thermometer in the heat sink, insert the top cover to enclose the system. Measurements were taken in an incremental form for every test to ensure accurate results, starting from 10% to 100%. At each stage a period of 8 minutes was waited to take the measurements of the resistor and heat sink. This method of gathering data allows the most accurate testing because of the fact that it has an order that can be repeated easily every time. Thermal images of the heat sink (see figure 5) were also taken at each stage by removing the top cover of the inverter casing as quick as possible and putting it back as fast as possible. The locations for the testing were always the same to ensure the same ambient temperature for each test.

Figure 3: Position for thermometer

Figure 4: Heat sink measurement locations



Figure 5: Thermal image

B. Simulation

To simulate and analyze the heat transfer of the experimental PCB design, FEMM (Finite Element Method Magnetics) software was used. This program solves low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. It also solves steady state heat flow problems which was the tool used to simulate the heat flow of our experimental design. There are certain details that must be known to be able to build and simulate our design. Most importantly is know the measurements of the devise been simulated and the material been used. Every material has their own thermal properties but for our case knowing the thermal conductivity, volumetric heat capacity, and volume heat generation if any is what is needed by the program when adding new materials. FEMM includes a library of materials ranging from solids, liquids, and gases, but not all materials that are needed are found. The materials that are needed to simulate our heat generation of the GaN transistor are gallium nitride for the semiconductor die and its casing which is taken to be FR-4 material. Connected to the semiconductor die is a thermal pad which is made of silicon to better dissipate the heat generated by the gallium nitride. For the PCB, copper pure is used for the thermal vias as well as the heat spreading layers. FR-4 material is used between each copper layer. The heat sink is simply made of copper pure. Around the entire model a big block is created to be able to simulate the room temperature surrounding it. Figure 5 shown part of the simulation with the thermal vias and the heat sink configuration for design #1 in FEMM. Two more simulation designs (design #2 and design #3) were made, as seen on figure 6 and 7 to try and see if a different configuration would improve heat dissipation of the GaN transistor. Model #2 eliminates the use of thermal vias and only uses one horizontal copper layer that connected to two more vertical copper layers connected to the heat sink, this way the GaN transistor is cooled through the top instead of the bottom. Model #3 uses a combination of the previews two models, it uses the thermal vias as well as the vertical copper blocks.

Figure 5: FEMM simulation design #1

Figure 6: FEMM simulation design #2

Figure 7: FEMM simulation design #3

Because 10 measurements were taken from the experiment, 10 different measurements must be made in the simulation to compare them with the experimental results. To do this one must first calculate the volumetric heat generations for the GaN die at a certain power. As the name implies, the volume for the GaN die must be calculated and by dividing the power by the volume we obtain the heat generation. To make the simulation as real as possible the temperature for the heat sink must match the temperature of the experimental for the same power value of the GaN. By applying borders to the heat sink it is possible to give a predetermined temperature. Ones the temperature of the heat sink and the volumetric heat for the GaN die are applied run the simulation to see what temperature reading results in the GaN die. The temperature reading of the die is the one to be compared with the resistors temperature of the experiment. Measurement values for FEMM design #1 are given in table 2.

Table II. Measurements

|  |
| --- |
| **GaN die measurements** |
| Length (mm/mils) | 2.13/83.86 |
| Width (mm/mils) | 6.00/235 |
| Height (mm/mils) | 0.225/8.89 |
| **GaN package measurements** |
| Length (mm/mils) | 8.63/339.76 |
| Width (mm/mils) | 6.00/235 |
| Height (mm/mils) | 0.45/17.72 |
| **Silicon thermal pad measurements** |
| Length (mm/mils) | 2.13/83.86 |
| Width (mm/mils) | 6.00/235 |
| Height (mm/mils) | 0.04/1.35 |
| **Thermal vias measurements** |
| Area (mm/mils) | 0.05/2.05 |
| Height (mm/mils) | 1.61/63.5 |
| **PCB heat spreading copper layers** |
| Length (mm/mils) | 22.99/905.28 |
| Width (mm/mils) | 6.00/235 |
| Height (mm/mils) | 0.04/1.4 |
| **Heat sink measurements** |
| Length (mm/mils) | 50.8/2000 |
| Width (mm/mils) | 6.00/235 |
| Height (mm/mils) | 19.05/750 |

C. Theoretical

Theoretical analysis was used to further corroborate the results of the experiment and simulation. Because three different simulation models were made, three theoretical analysis where made. To be able to better visualize and calculate the temperature of the resistance of each model, an electric circuit was made. The power dissipation of the resistor is represented as a current that passes through a resistance and reaches a source. The resistance represents the thermal resistance of the PCB configuration and the source represents the temperature of the heat sink. Figure 8a represents design #1, 8b represents design #2, and 8c represent design #3. By multiplying the power dissipated by the resistance and adding the heat sink temperature, we find the resistor temperature.



Figure 8 (a)



Figure 8 (b)



Figure 8 (c)

For design #1, one must calculate the thermal resistance for the thermal vias. Thermal resistances for any design imply knowing the resistivity of the material been used (98.1811 for copper) and multiplying it by the height over area. This first analysis with the thermal vias was thought as cylinders with inner diameter and outer diameter instead of separate blocks like the simulation. This way the results will be more accurate with the experimental model. The area of the vias were calculates as shown in equation 2a and the thermal resistance for the vias with equation 2b. To obtain the resultant temperature for the resistor one simply multiplies the power dissipation (P) of the resistor by Rtotal and adds the temperature of the heat sink (Th) as shown in equation 3. For design #2 the geometry was simplified, first the area of two rectangles (equation 4a) are calculated and by knowing their height and we can then calculate their equivalent resistance (see equation 4b) and simplify the resistances to solve the circuit in figure 8b. Finally for design #3 one uses the same thermal equivalent resistances of the previous two models to find an equivalent resistance (see equation 5) and solve the circuit in figure 8(c).

 A = π($\frac{Outer diameter }{2}$)2 – π($\frac{inside diameter}{2}$)2 (2a)

 R1 = $\frac{98.1811\frac{H}{A}}{90}$ ; Rtotal = R1 (2b)

Resistor temp = (Rtotal)(P) + (Th) (3)

A = LW (4a)

R2,3 = 98.1811$\frac{H}{A}$ (4b)

Rtotal = R2 ‖ R3 (4b)

Rtotal = R4 + R5 ‖ R6  (5)

# Results and Discussion

For the experimental results of the resistor, three different tests were made and each resulting captures at 8 minutes. Power dissipation started from 10% to 100%. The results for the thermostat reading on the resistor are shown in table III. The temperature readings for the heat sink were taken at a different moment. The resulting temperature readings for the middle, bottom middle, and bottom side (refer to figure 3) of the heat sink are listed in table IV. Table V shows the resulting resistor temperatures for the different simulation models and table VI for the theoretical calculations.

Table III. Experimental resistor temperature

|  |  |
| --- | --- |
| Power | Temperature (˚K) |
| 17.96 | 363.43 |
| 16.27 | 356.96 |
| 14.41 | 348.92 |
| 12.61 | 341.00 |
| 10.84 | 333.80 |
| 9.00 | 325.76 |
| 7.21 | 317.98 |
| 5.48 | 317.33 |
| 3.64 | 326.25 |
| 1.83 | 310.00 |

Table 3 shows the experimental resistor temperature to be used to compare with the simulation and experimental results. Other measurements for the resistor were made at different locations but resulted in inaccurate measurement values when compared to the simulation and theoretical analysis. By measuring at a point closest to the connection between the resistor surfaces mounting area a more accurate result was obtained.

Table IV. Experimental heat sink temperature

|  |  |  |  |
| --- | --- | --- | --- |
| Power (W) | Middle (˚K) |  Bottom middle (˚K) |  Bottom side (˚K) |
| 17.96 | 316.6 | 308.9 | 324.4 |
| 16.27 | 314.6 | 307.2 | 321.4 |
| 14.41 | 311.9 | 305.3 | 318.1 |
| 12.61 | 309.4 | 303.6 | 314.7 |
| 10.84 | 306.3 | 301.9 | 311.8 |
| 9.00 | 304.1 | 300.3 | 308 |
| 7.21 | 301.7 | 298 | 305.4 |
| 5.48 | 299.8 | 297.3 | 302.6 |
| 3.64 | 314.4 | 307 | 316.4 |
| 1.83 | 302.3 | 298.7 | 304.8 |

Table IV shows the resulting experimental temperature readings of the thermometer for the heat sink at three different locations. Three different locations were used to check and see if significant temperature reading occurred. It was also done to be able to compare the temperatures with the thermal camera readings. Thermal camera readings are not the most accurate, but it was used as a reference to see if there was a bogus measurement with the thermometer. Measurements readings of the thermometer at the middle of the heat sink matched the thermal camera readings the most. This was to expect because the thermal camera measures the outer parts of the heat sink.

Table V. Simulation resistor temperatures

|  |  |  |  |
| --- | --- | --- | --- |
| Power (W) | Design #1 (˚K) | Design #2 (˚K) | Design #3 (˚K) |
| 17.96 | 363.88 | 661.94 | 567.06 |
| 16.27 | 357.66 | 627.28 | 541.55 |
| 14.41 | 350 | 589.1 | 514.56 |
| 12.61 | 342.53 | 552.03 | 487.99 |
| 10.84 | 336.46 | 515.98 | 460.27 |
| 9.00 | 328.36 | 479.12 | 432.65 |
| 7.21 | 322.49 | 442.61 | 405.74 |
| 5.48 | 316.65 | 407.39 | 379.86 |
| 3.64 | 326.11 | 387.72 | 369.11 |
| 1.83 | 310.25 | 341.22 | 331.32 |

Table V list the resulting GaN transistor temperature obtained in FEMM software for each design at their corresponding power output. Design #1 keeps the resistor cooler better across all power stages.

Table VI. Theoretical resistor temperatures

|  |  |  |  |
| --- | --- | --- | --- |
| Power (W) | Design #1 (˚K) | Design #2 (˚K) | Design #3 (˚K) |
| 17.96 | 359 | 730 | 584 |
| 16.27 | 353 | 689 | 557 |
| 14.41 | 346 | 643 | 526 |
| 12.61 | 339 | 599 | 497 |
| 10.84 | 332 | 556 | 468 |
| 9.00 | 326 | 511 | 438 |
| 7.21 | 319 | 468 | 409 |
| 5.48 | 313 | 426 | 382 |
| 3.64 | 323 | 398 | 369 |
| 1.83 | 308 | 346 | 331 |

Table VI shows the resulting resistor temperatures for the theoretical analysis. Ones more, design #1 show the lowest temperatures across the power dissipation stages. This result also ensures us that the simulation for each design is as accurate as possible.

# Conclusion

Power inverters will keep evolving the same way technology that uses them evolves. With the popularity of solar plates and wind turbines growing, the use of power inverters will grow too. Each year more and more vehicle manufacturers are producing electric vehicles (EVs) and power inverters are at the center of all. Domestically power inverters are used to power many home applications and even as emergency generators. To be able to build a power inverter that is smaller for applications such as electric vehicles, solar, or wind were their current size can be 10 times bigger many things have to be taken into consideration and thermal managements is one of them. The use of the GaN power transistor was used on the experimental prototype analyzed because of its improvements in thermal management, switching speeds, high dielectric strength, high operating strength, high current density, and high band gap. To further improve the temperature management of the GaN transistor three simulation where made to see which one lowered the heat been dissipated by the transistor. Three simulations where created to corroborate and compared with theoretical analysis. At the end it was found that the current cooling configuration in the experimental prototype was the best way of cooling the gallium nitride power transistor.

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